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Introduction

There is a wealth of recorded data about trawl boards - their spreading force, stability, behaviour on rough ground (Main and Sangster, 1979) and their power requirements in relation to fuel economy (Anon, 1974). In addition to these mechanical aspects it is recognised that the "herding" of fish by ropes and bridles plays a part in the catching process. Bagenal (1958) for instance showed that bottom contact and the length and angle of attack of bridles were important, while Hemmings (1973) described the herding action of the ropes of the Danish seine-net.

Other aspects play a part; for instance Korotkow and Martyschewski (1977) used the "Atlant" and "Thetis" submersibles to observe fish reactions to sand clouds on fishing grounds in the North Sea and Central Eastern Atlantic. From these observations, made in daylight, they concluded that fish could see or sense sand clouds and were effectively herded into the path of the net. Casual observations by the present authors in 1979 and 1980 on haddock, cod, whiting, saithe, dogfish, skate, sandeels, gurnards and flatfish confirm these reactions. Sabourenkov (1977) discussed the escape of fish through the gap between the trawl board turbulence trails (sand clouds) and the wing-ends of the trawl.

Though these are daylight observations, the effect may be important by night also and in deep water, since bioluminescence (Herring, 1978) will make the turbulent zones visible.

In view of these interesting considerations, it was decided to make a study of the sand clouds generated by different types of trawl board, and this paper describes the results.

Material and Methods

Experiments were carried out during the summers of 1978 and 1979 on fishing grounds off Lossiemouth, Scotland, on four types of trawl board with twin 27.5 m and twin 55 m bridles. The fisheries research vessel "Mara" (200 hp, 22 m) was used as a side trawler, and towing the divers' Towed Underwater Vehicle (TUV II) (Main and Sangster, 1978) shown in Plate I. The depth ranged from 26 to 30 m and the seabed was flat sand. The length of trawl warp aft was 137 m of 15 mm wire, an acceptable gear geometry being obtained in this depth of water. Ship speed was kept as near 1.5 m s^{-1} (3 knots) as possible using a speed log, both on board the towing vessel and on TUV II. The method of deployment of TUV II alongside fishing gear was as described by Main and Sangster (1978a, 1979).

Plate I. The Towed Underwater Vehicle (TUV II) being paid out on its towing warp from the stern of FRV "Mara".

The four types of trawl boards used during the experiments are indicated in Table I, their design specifications being as described in the FAO Fishing Manual (Anon, 1974).

Performance can vary considerably depending on the way the otterboard is rigged, and so a common method of commercial rigging was used throughout the experiments. The behaviour of each type of board and its performance on both smooth sand and rough ground were described in detail by Main and Sangster (1979). The net used was the "Lossie Q" bottom trawl, a version of the Aberdeen 4-panel series described by Corrigall and Watson (1977). Board spreads were measured using a hand-held sonar unit, model 6400, manufactured by Helle Engineering of Dyce, Aberdeen, Scotland. This lightweight echosounder is designed to locate objects under water and a visual LED display gives accurate distance readings up to its maximum range of 110 m. In operation, one diver aimed the instrument towards the starboard trawl board while the pilot manoeuvred the vehicle into position alongside the port board. Readings of board spread were transmitted by voice to the towing vessel, via a cable communication system, model 322D, designed by Helle Engineering.

Table I
Board Type, Area and Weight

Door	Size Overall Length and Overall Breadth	Projected Area m^2	Wt in Air kg	Wt in Seawater kg
Rectangular Flat (Wooden)	1.7 m x 0.99 m	1.6	102	52
Rectangular Cambered (Steel Low Aspect Ratio)	1.7 m x 0.89 m	1.5	158	113
Polyvalent (Oval Cambered Slotted Steel)	1.7 m x 1.05 m	1.7	216	162
Rectangular Vee (Steel)	1.7 m x 1.00 m	1.7	156	145

The spread across the wing-ends of the net was measured in a similar manner, the measurement being obtained by "bouncing" the sonar signal off a small plastic trawl float attached to the wing-end. Wing-end height was obtained by holding the sonar unit in the vertical mode, thus reflecting the signal off the seabed.

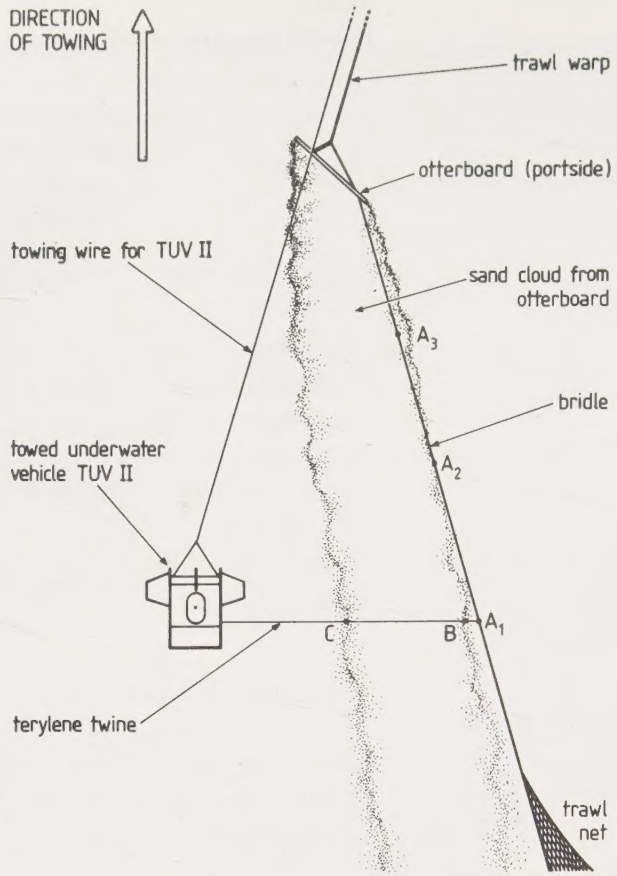
Reference marks (wire screw grips) were attached to the top bridle on each side of the gear 5.5 m, 9 m, 18 m and 27.5 m behind the backstrops for the twin 27.5 m bridle experiments and extra marks at 41 m and 55 m on the longer bridles.

Sand cloud heights were measured at each of the marked positions and at the join of the backstrops to the twin bridles, using the hand-held sonar unit in the vertical mode.

A reel of pre-stretched terylene twine, marked at 0.25 m intervals, was attached to the side of the TUV II. The line had a quick-release clip tied firmly to the end. At each marked position on the top bridle, one diver attached the clip in front of the screw clamp, then gave instructions to the pilot to move horizontally, either port or starboard, to position the vehicle at the inside or outside edge of the sand cloud. In this way, the length of line paid out from the vehicle measured the distance from the edges of the cloud to the mark on the bridle. This technique is illustrated in Figure 1, which also defines the inner and outer edges of the sand clouds.

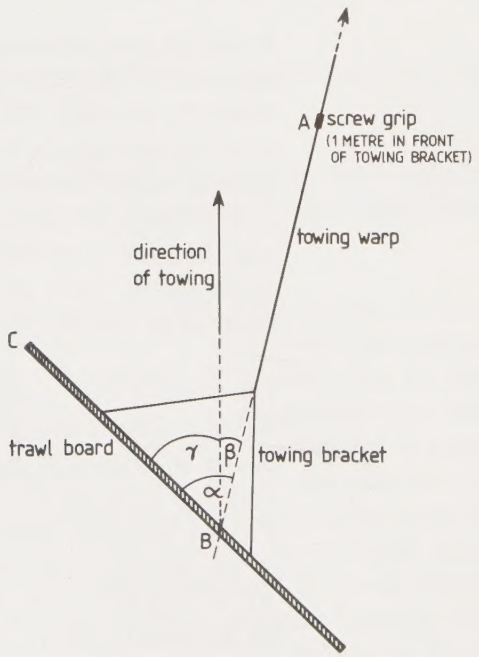
The angle α of the board to the towing warp (Fig. 2) was measured by fixing a wire screw grip to the towing warp one metre in front of the board. A length of twine with a quick release clip tied to one end was attached in front of the screw grip by one diver and pulled tightly back to a point half way down the leading edge of the otterboard. The line was cut at the leading edge and later measured on board ship, giving the distance AC of Figure 2. AB, AC and BC are thus all known, and triangle ABC can be accurately drawn and angle α calculated.

A typical dive routine was to measure the angle of attack and the spread between the boards, then continue by measuring the sand cloud edge distances and heights at the fixed marks along the bridles, and complete the dive by measuring wing-end spread and height.



A_1B – distance from inner edge of sand cloud to marked position on warp
A_1C – distance from outer edge of sand cloud to marked position on warp
A_1, A_2, A_3 – marked positions on bridle

Figure 1. Sketch drawing demonstrating the technique used by the divers in the Towed Underwater Vehicle, for obtaining linear measurements of the sand cloud edges to the marked positions on the warp.



α – angle of otterboard to towing warp
β – angle of towing warp to direction of tow
γ – angle of attack of otterboard to direction of tow

Figure 2. Sketch drawing (plan view) explaining the method used to calculate the angle of attack (a) of the otterboard to the towing warp.

Measurements were made of both port and starboard sand clouds to check the symmetry of the gear, although the area was known to have small tidal flow. A DAFS Marine Laboratory heel and pitch meter was attached to the face of each board to check that the boards were stable and in contact along the full length of the keel. These self-recording instruments provided a continuous record of the board attitude during each experiment.

Speed log measurements were regularly passed by voice to the towing vessel, to be recorded there.

The sand clouds were recorded on video tape from the TUV II by a diver-held, low-light television camera fitted with an RCA Sitcon tube (Main and Sangster, 1979; Wardle and Priestley, 1976; Anon, 1979). These recordings were used to make drawings showing the directions of flow within the sand clouds.

Seabed samples to a depth of 5 cm were collected from each end of the tow and analysed for particle size using the technique described by McIntyre and Murison (1973).

Results

Heel and pitch

The pitch readings (angle of deviation from the horizontal) taken from the heel and pitch meter traces showed that the full lengths of the keels of all the boards remained in continuous contact with the seabed. This was confirmed by direct observation at the start of each set of experiments. The angle of heel (angle of deviation from the vertical, either inwards or outwards) for the rectangular flat and cambered boards did not vary more than 2° from the vertical. During towing, the polyvalent and Vee boards lay inwards at angles of 5° and 3° respectively. These figures are the same for both bridle lengths.

Angle of attack

The angle of attack γ is the angle between the board face and the direction of tow as seen from directly above. The angle α between the board face and the towing warp is measured as already described.

The angle β between the towing warp and the direction of tow is obtained from:-

$$\sin \beta = \frac{\text{½ board spread}}{\text{warp length}}$$

The angle of attack is thus easily obtained, since

$$\gamma = \alpha - \beta$$

Table II shows the angle of attack γ of the boards.

Table II
Angle of Attack of Each Type of Board

Bridle Length	27.5 m	55 m
Rectangular flat	41°	44°
Rectangular cambered	34°	37°
Polyvalent	37°	41°
Rectangular Vee	41°	44°

Wing-end height

The wing-end height of the net was between 2.5 m and 2.1 m in all the experiments

Bridle angle

In order to map the sand clouds and include on the same plan the boards, bridles and wing-ends, values are required of the bridle angle Θ
This was calculated using the formula:-

$$\sin \Theta = \frac{\frac{1}{2} \text{ (board spread - wing-end spread)}}{\text{bridle length}}$$

and the results are given in Table III.

Table III
Bridle Angle of Each Type of Board

Bridle Length	27.5 m	55 m
Flat	10½°	9½°
Polyvalent	12°	10½°
Cambered	12°	11°
Vee	10½°	9½°

Sand cloud geometry

Each set of measurements taken on a dive was used to prepare a plan and elevation showing the relationship between the boards, warps, bridles and sand clouds. From these plans were calculated at each of the fixed positions on the bridles the lateral spreading velocity (Figs. 3 to 6) and the lateral inward distance (Figs. 7, 8) of the edges of the sand clouds, as well as their cross sectional width and height (Figs. 9, 10). It was found that the clouds from the Vee and rectangular flat boards just passed through the wing-ends of the net, when the shorter 27.5 m bridles were used. In all other cases the sand cloud passed well outside the wing, as exemplified in Plate II.

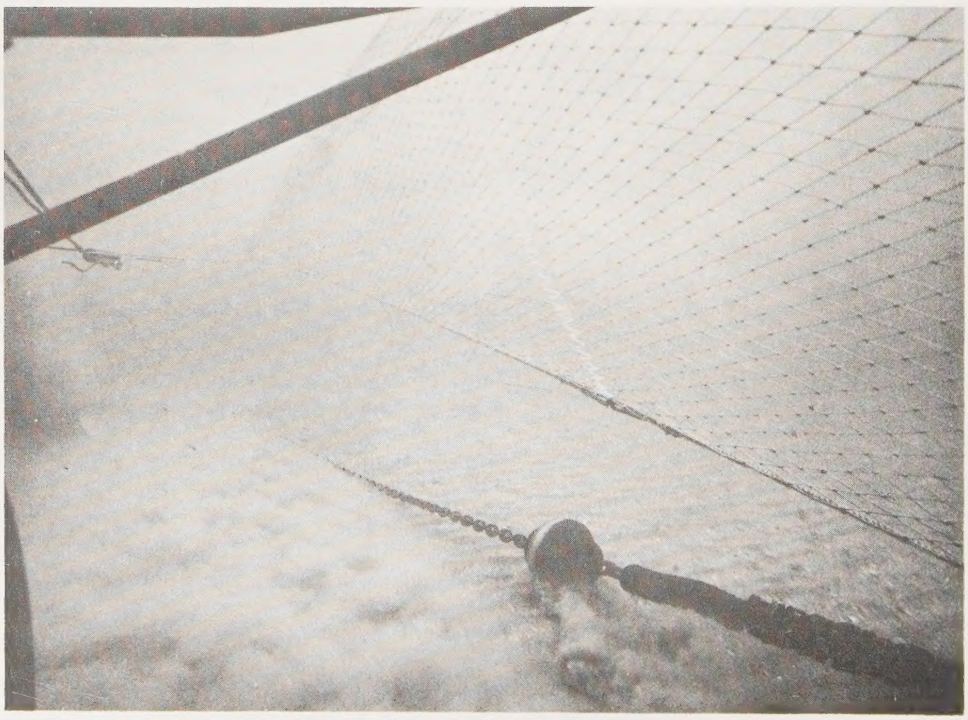


Plate II. The clear water corridor between the port wing of a 4-panel trawl and the sand cloud, viewed from the Towed Underwater Vehicle.

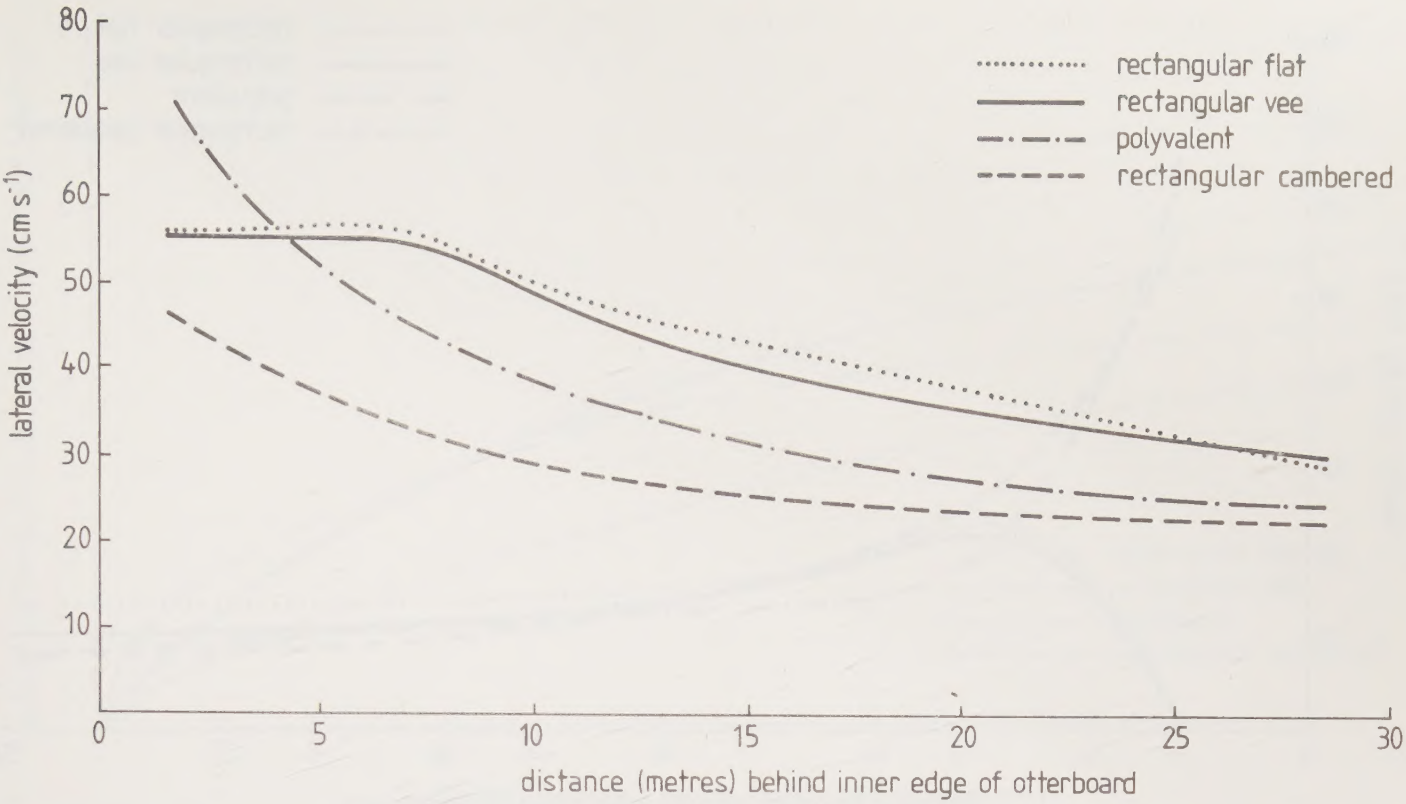


Figure 3. Lateral velocity of inner edge of sand clouds from all boards with twin 27.5 m bridles.

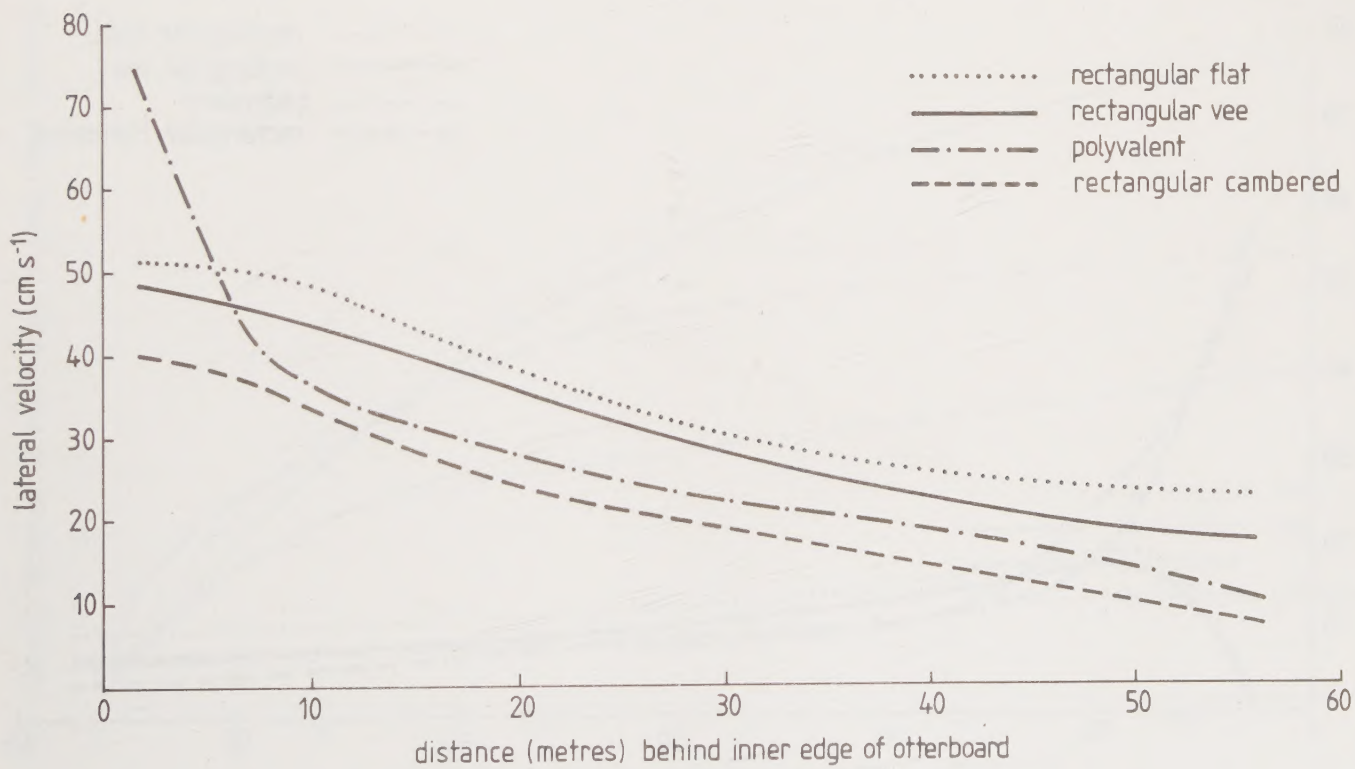


Figure 4. Lateral velocity of inner edge of sand clouds from all boards with twin 55 m bridles.

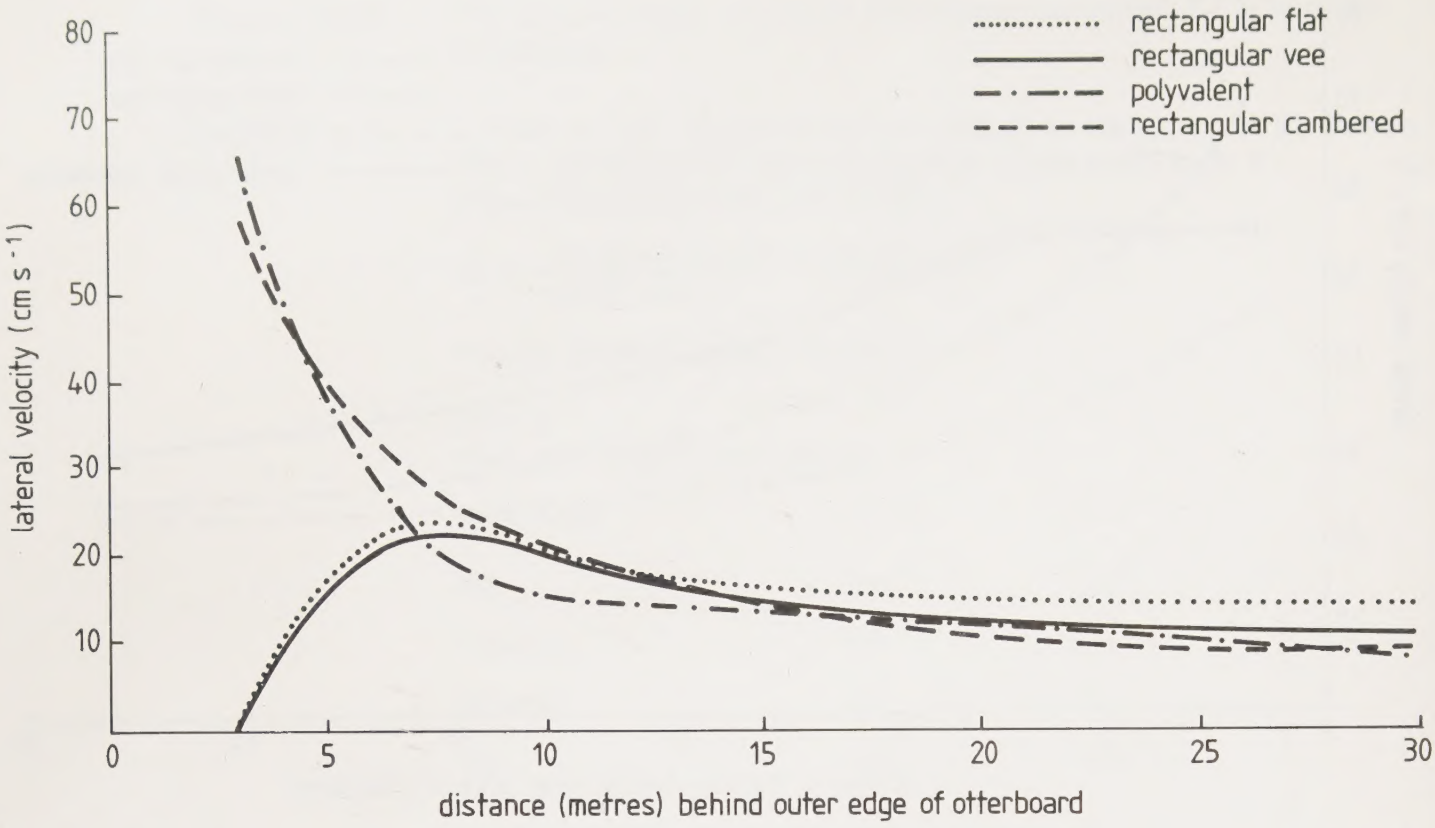


Figure 5. Lateral velocity of outer edge of sand clouds from all boards with twin 27.5 m bridles.

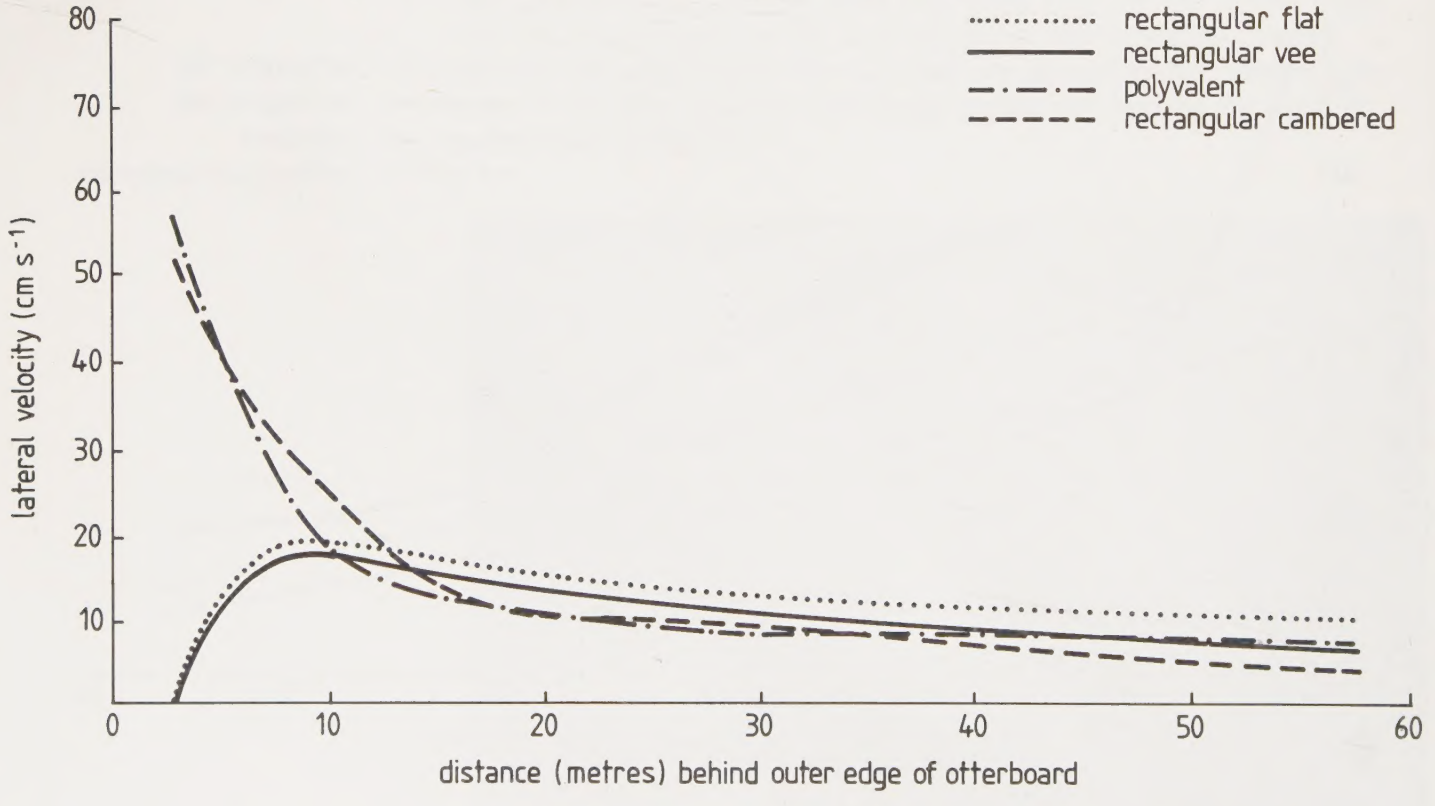


Figure 6. Lateral velocity of outer edge of sand clouds from all boards with twin 55 m bridles.

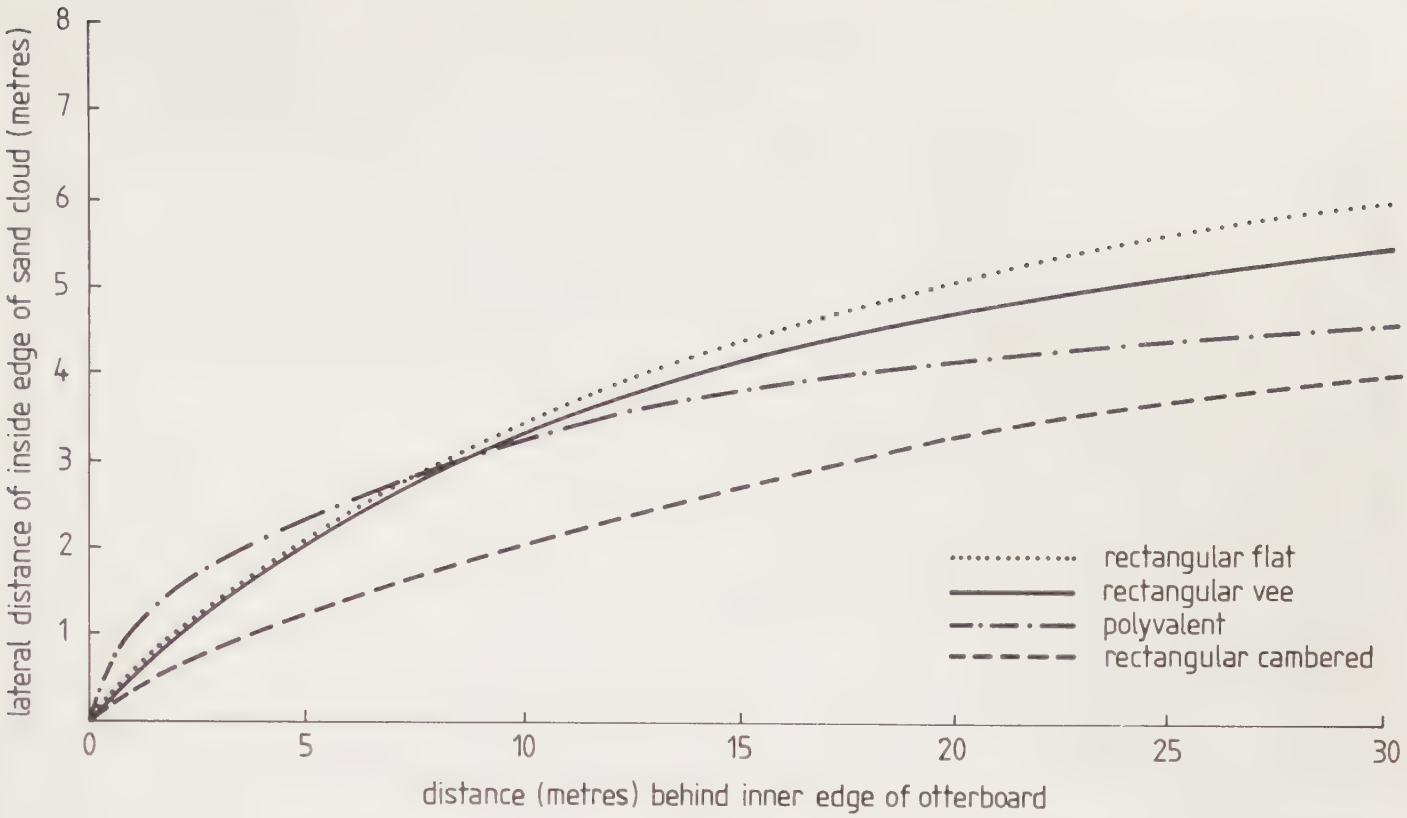


Figure 7. Lateral inward distance of inside edge of sand clouds from all boards with twin 27.5 m bridles.

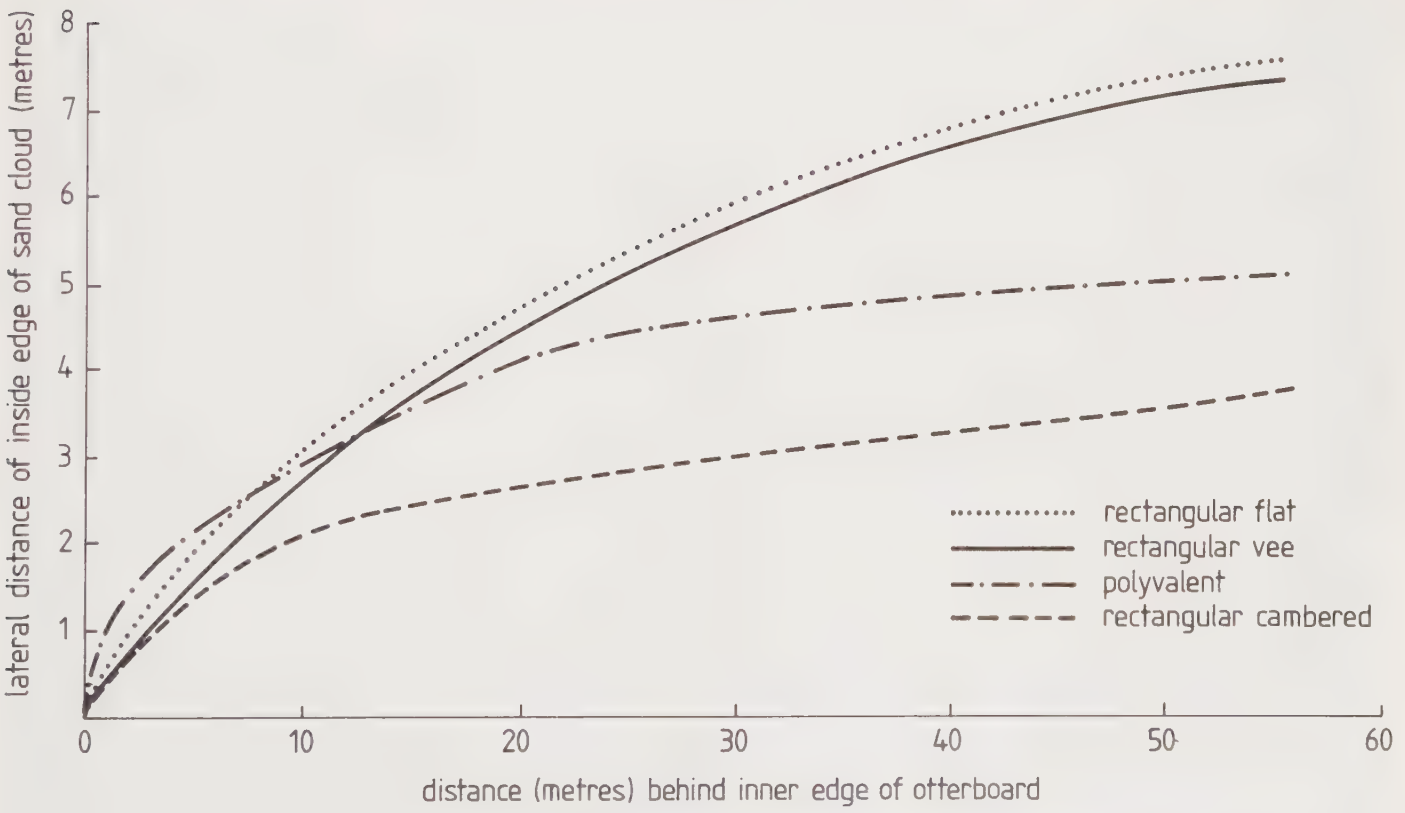


Figure 8. Lateral inward distance of inside edge of sand clouds from all boards with twin 55 m bridles.

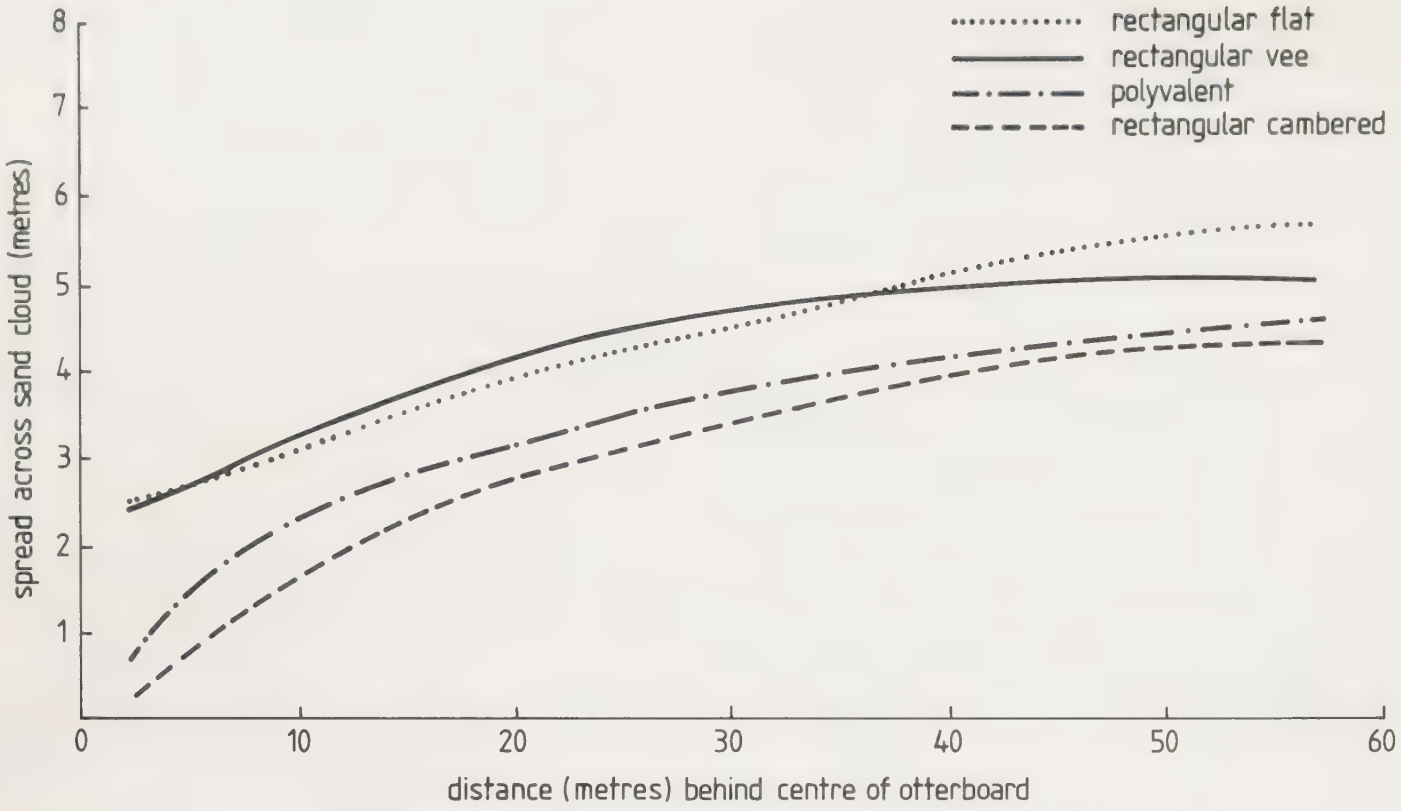


Figure 9. Width of sand clouds from all boards with twin 55 m bridles.

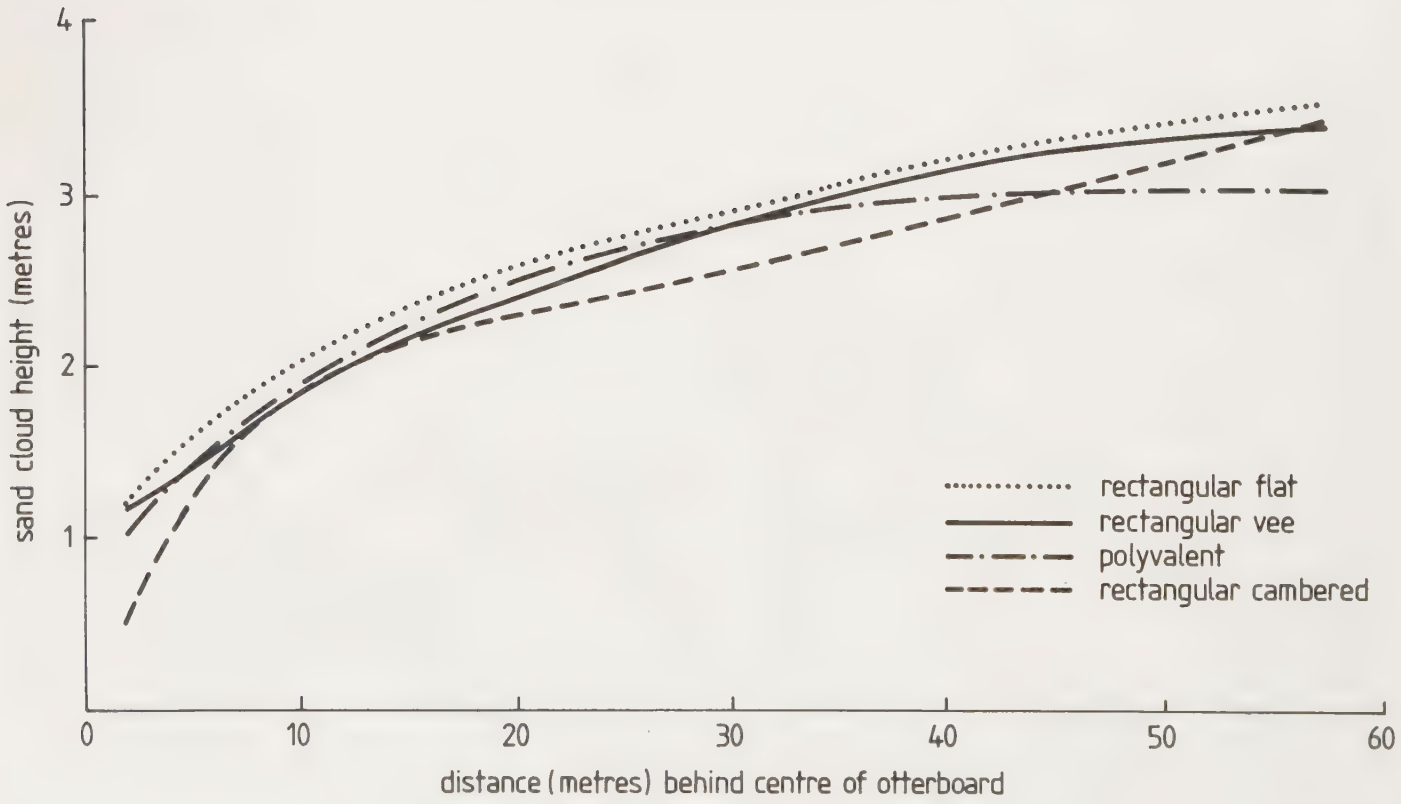


Figure 10. Vertical height measurement of sand clouds from all boards with twin 55 m bridles.

On several occasions fish were seen to pass over the lower bridle into the clear corridor between cloud and wing.

The figures shown in Table IV, taken from Figures 3 and 4 show that the sand clouds are still spreading slowly inwards as they pass the wing-end.

Table IV
Lateral Spreading Velocity of the Inner Edge of Sand Clouds at the Wing-end of the Net

Bridle Length	27.5 m	55 m
Flat	0.29 m s^{-1}	0.23 m s^{-1}
Cambered	0.23 m s^{-1}	0.08 m s^{-1}
Polyvalent	0.25 m s^{-1}	0.10 m s^{-1}
Vee	0.31 m s^{-1}	0.17 m s^{-1}

It is reasonable to suppose that the lateral spreading velocity of the sand cloud may change with towing speed, but higher speeds could not be tested with this rig as "Mara's" power was inadequate.

Sand cloud behaviour

As well as the accurate measurements made of the shape and size of the sand clouds, the video tapes show the flow within the sand clouds as they are formed and developed. Plates III to VI illustrate this, and Figs. 11 to 14 are drawings showing the appearance of the sand cloud for each type of board.

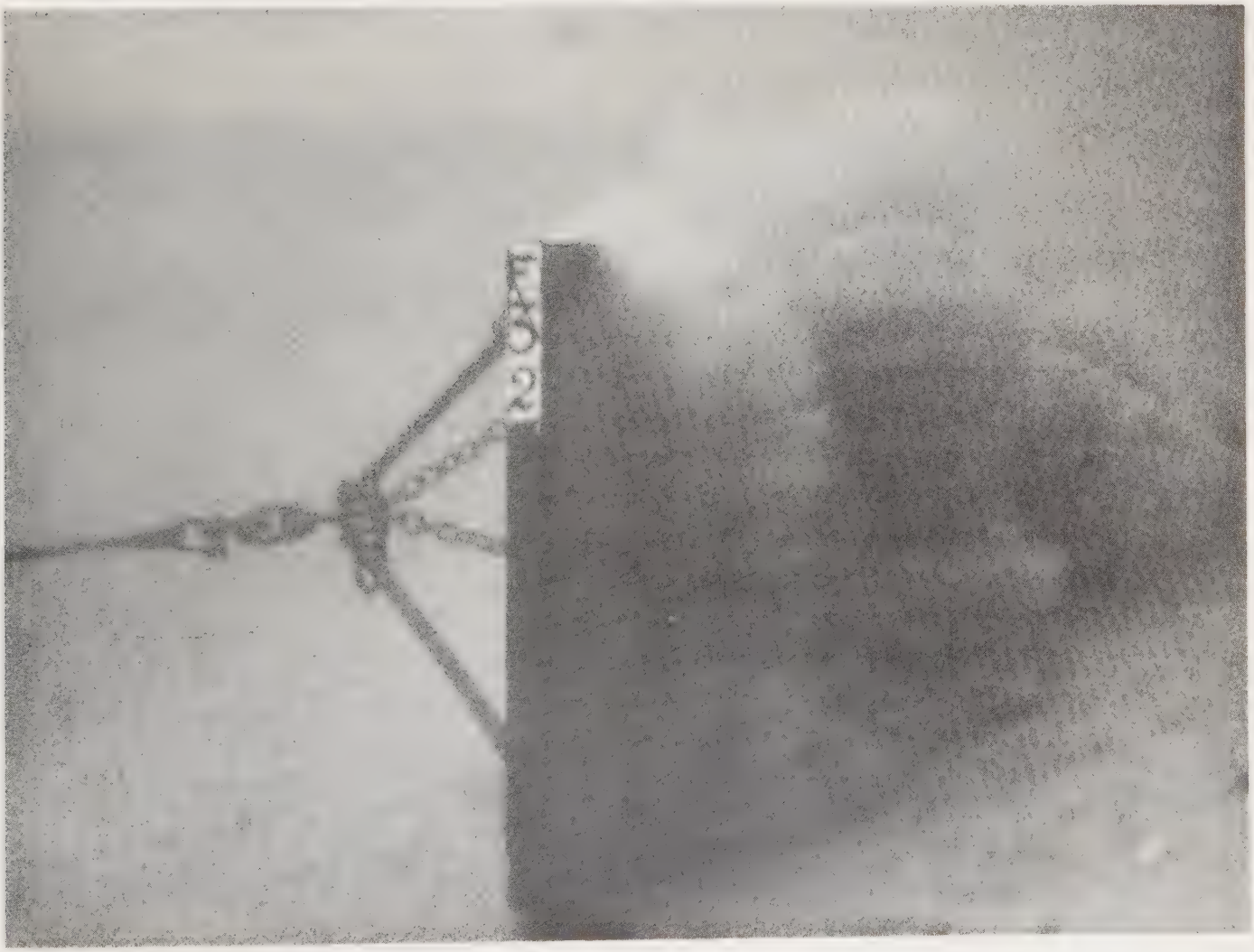


Plate III. Rectangular flat trawl board showing large sand cloud filling the rear of the board.

Plate IV. Rectangular cambered board showing the very low sand cloud pattern immediately behind the board.

Plate V. Vee board showing the large sand cloud produced behind the board.

Plate VI. Polyvalent board showing the sand cloud being deviated inwards along the bridles.

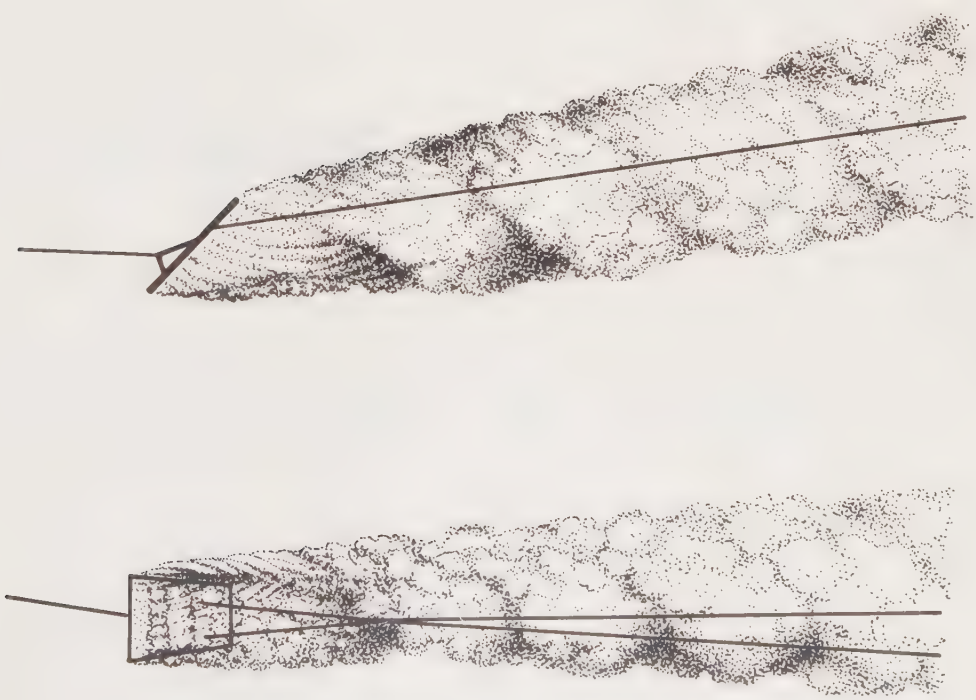


Figure 11. Line drawings of sand clouds from rectangular flat boards.

Figure 12. Line drawings of sand clouds from rectangular cambered (low aspect ratio) boards.

Figure 13. Line drawings of sand clouds from oval cambered slotted (polyvalent) boards.

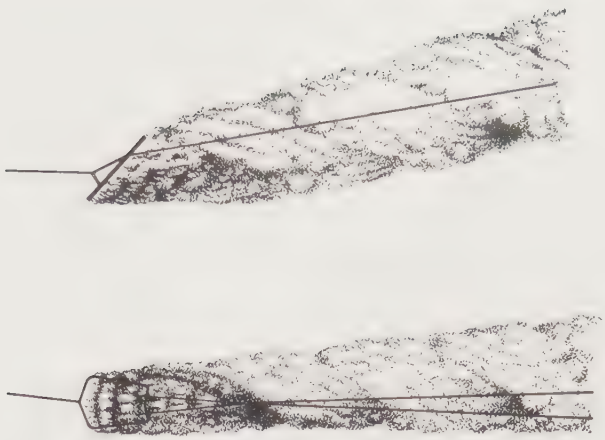


Figure 14. Line drawings of sand clouds from rectangular Vee type boards.

The sand clouds generated by the otterboards were measured only while towing in line with and against the tide. Tidal flow over the seabed during these experiments was very small and no significant differences could be observed in the divers' measurements of the sand clouds at any state of the tide.

Seabed sediment analysis

The sediment at both ends of the tow consisted of fine sand with small amounts of organic material. The fraction of fine clay material was extremely small (0.3%), being slightly greater at the west end of the tow. The sand was finer at the west than at the east end of the tow (Median diameter of sediment = 169 and 185 μm respectively). The results are summarised in Figure 15.

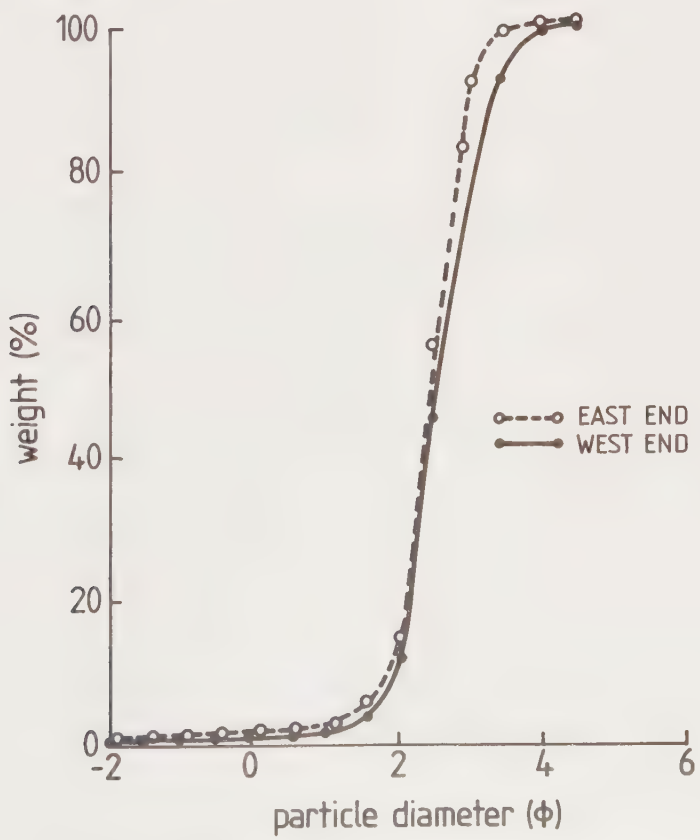


Figure 15. Composition of seabed sediments from the line of tow.

The overall conclusion drawn from the sediment analysis is that the sand at the west end of the tow was finer but with slightly coarser elements than at the east end, which was slightly coarser but better sorted. Measurements of the sand cloud did not show any related differences.

Discussion

Comparing the shape of the sand clouds

It can be seen from the scaled plan views in Figs. 12 and 13 that the polyvalent and cambered boards produce a narrower sand cloud than the flat and vee boards (Figs. 11, 14). The cloud starts narrower, and remains narrower right up to the wing-end. Note from Table I that the boards are all very similar in size.

The cloud behind the cambered board is particularly low and does not reach the same height as the other boards until approximately 7 m along the bridles (Fig. 10). The streamlined flow around the back of the cambered board does not draw the cloud in behind the board and gives less immediate turbulence at this point. The clouds from all the boards show a rapid increase in height and width soon after the board moves on, and the sand cloud is still spreading at the wing-ends (Table IV), after which the rate of increase is much slower and the height is increasing less than the width (Figs. 9, 10). It can be seen from Figure 10 that at distances greater than 20 m behind the boards the sand clouds are just higher than the top of the wing-ends (2.1 m) of this net. Therefore, from that point the sand cloud could have a herding influence equal to that of the netting panel of the wing. This would be true with bridles up to 55 m. However, we are unable at the moment to predict what would happen beyond 55 m. Casual observations have shown that the cloud will thin and the height will decrease as the sand particles begin to settle back to the seabed, so the settling rates of the seabed materials could become important.

The appearance of the sand cloud, but not its size, is governed by the type of seabed. Brief observations on different seabed types show that soft, light-coloured mud produces the most opaque and reflective type of cloud and the fine mud remains in suspension much longer than coarse sand. When the board passes over small patches of hard ground no cloud is generated but larger particles are seen sucked up which immediately settle (Main and Sangster, 1979) (Plate VII).

Inner edge of sand cloud

Figs. 3 and 4 show that the speed of lateral expansion of the sand clouds from the inner edges of all four types of boards are initially rapid. The inner edge of the polyvalent board sand cloud moves furthest towards the track of the gear immediately behind the board. The slot openings in the polyvalent boards are intended to increase its hydrodynamic efficiency by reducing the suction turbulence on the back surface (Anon, 1974). This more efficient water flow around this board probably increases the lateral displacement of the inner edge of the sand cloud, immediately behind the board. After approximately 20 s, some 30 m behind the polyvalent and cambered boards, the spreading velocity of the sand cloud becomes insignificant in relation to the towing speed. At 30 s or 50 m this is true of all the boards.

Plate VII. Polyvalent board on hard ground showing the absence of the normal sand cloud pattern.

Outer edge of sand cloud

The initial behaviour of the outer edge of the sand clouds from the polyvalent and cambered boards differs completely from those of the rectangular flat and Vee boards (Figs. 5, 6). In the first 2 s after the flat and Vee boards have moved on there is no lateral movement, but during the next 4 s, the outer edge begins to move inwards towards the bridles. This movement reaches a peak speed of approximately 0.2 m s^{-1}, 6 s after the board has passed. A gradual deceleration then takes place, and the inward movement becomes negligible by the time the wing-end of the net passes.

With polyvalent and cambered boards rapid inward lateral velocities occur immediately behind the boards, with peak speeds of approximately 0.6 m s^{-1} reached only 2 s after the board has passed. A steady deceleration to approximately 0.2 m s^{-1} then takes place for 4 s and velocity continues to decrease back to the wing-end of the net.

Critical bridle angle

From Fig. 8 it is easy to deduce, for any board and any bridle length, the *critical bridle angle.* This is the bridle angle at which the sand cloud just touches the wing-end of the net. This crucial information is given in Table V for the particular bridle lengths used in the experiments.

Table V
Bridle Angles for Wing-ends of Net to Touch Sand Cloud Using Lateral Distance Values

Bridle Length	27.5 m	55 m
Rectangular Flat	11.5°	8°
Rectangular Cambered	8°	4°
Oval Cambered Slotted (Polyvalent)	9°	5.5°
Vee	11°	7.5°

These bridle angles are practical settings using the "Lossie Q" gear with 27.5 m bridles. The very small angles predicted for use with the cambered and polyvalent boards with 55 m bridles (ie 4° and 5.5° - see Table V) are, however, not practical without reducing the board spread.

It is noteworthy that the hydrodynamically efficient boards generate sand clouds that do not touch the wing-ends. It is well known that sweeps and ropes with no otterboard sand cloud will effectively herd fish into the mouth of Danish seine nets and pair trawls. The sweep or rope provides enough stimulus. The fish are gathered into the mouth of the net by herding from wide swept areas using single ground ropes or wires crossing the seabed at a small angle. It is also significant that nets with wing-end boards gave way to nets with bridles between board and wing-end because catches appeared to increase as the area swept between the boards increased. The placing of the sand cloud along the bridles and sweeps therefore seems a logical addition to the herding apparatus.

Correct bridle angle in relation to towing speed is essential for effective herding of larger fish into the mouth of the net leaving the smaller sizes behind. Too small a bridle angle could lead to the effective herding of the small fish and the loss of the important larger fish. For example, a combination of 3 to 4 knots (1.54 m s^{-1} to 2.06 m s^{-1}) forward speed with an approximate 1 knot (0.52 m s^{-1}) herding speed is obtained using a bridle angle of between 10 and 15°. This matches well with the performance of the shorter 27.5 m bridles and the less efficient flat and Vee boards with the "Lossie Q" trawl.

If the presence of a sand cloud does give some advantage, then the use of less efficient boards and the generation of extra sand clouds on the bridles in the clear corridors by other devices could in some circumstances be worthwhile.

It may be advantageous, also, to place additional small boards (similar to "pony doors") at a calculated distance along the bridles ahead of the trawl. These small boards should not decrease the spread of the gear and would create their own sand clouds to fill the gaps between the main sand clouds and the wing-ends.

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Summary Polyvalent, Vee, flat and cambered boards were used in experiments to study the behaviour and geometry of their sand clouds. The sand clouds created by the turbulence spread from the trawl board inwards along the bridles. The rate and extent of lateral movement is different for the inner and outer edges of the sand clouds produced by each type of board. The

sand clouds generated from the polyvalent and cambered boards are narrower in comparison to those of the flat and Vee.

With the data from these experiments, bridle angles can be predicted to ensure that the sand clouds pass through the wing-ends of the net. These bridle angles represent practical arrangements with shorter sweeps but not with the longer sweeps tested.

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